NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

DYNAMIC BANDWIDTH PROVISIONING USING MARKOV CHAIN BASED ON RSVP

by

Yavuz Sagir

September 2013

Thesis Advisor: Preetha Thulasiraman
Second Reader: Joshua D. Green

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** September 2013	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE DYNAMIC BANDWIDTH PROVISIONING USING MARKOV CHAIN BASED ON RSVP			**5. FUNDING NUMBERS**
6. AUTHOR(S) Yavuz Sagir			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT

An important aspect of wireless communication is efficiency. Efficient network resource management and quality of service (QoS) are parameters that need to be achieved especially when considering network delays. The cooperative nature of unmanned ground vehicle (UGV) networks requires that bandwidth allocation be shared fairly between individual UGV nodes, depending on necessity. In this thesis, we study the problem of dynamic bandwidth provisioning in a UGV network. Specifically, we integrate the use of a basic statistical model, known as the Markov chain with a widely known, network bandwidth reservation protocol, known as the Resource Reservation Protocol (RSVP). The Markov chain results are used with RSVP to identify specific bandwidth allocation requirements along a path such that data transmission along that path is successful. Using a wireless simulation program known as Qualnet, we analyze the bandwidth efficiency and show that this algorithm provides higher bandwidth guarantees and better overall QoS when compared with solely using RSVP in wireless communication networks.

14. SUBJECT TERMS Wireless Communication, Resource Reservation Protocol, Markov Chain Process, Dynamic Bandwidth Allocation			**15. NUMBER OF PAGES** 95
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

DYNAMIC BANDWIDTH PROVISIONING USING MARKOV CHAIN BASED ON RSVP

Yavuz Sagir
Lieutanant Junior Grade, Turkish Navy
B.S.S.E, Turkish Naval Academy, 2006

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRONIC WARFARE SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
September 2013

Author: Yavuz Sagir

Approved by: Preetha Thulasiraman
Thesis Advisor

Joshua D. Green
Second Reader

Dan C. Boger
Chair, Department of Information Sciences

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

An important aspect of wireless communication is efficiency. Efficient network resource management and quality of service (QoS) are parameters that need to be achieved especially when considering network delays. The cooperative nature of unmanned ground vehicle (UGV) networks requires that bandwidth allocation be shared fairly between individual UGV nodes, depending on necessity. In this thesis, we study the problem of dynamic bandwidth provisioning in a UGV network. Specifically, we integrate the use of a basic statistical model, known as the Markov chain with a widely known, network bandwidth reservation protocol, known as the Resource Reservation Protocol (RSVP). The Markov chain results are used with RSVP to identify specific bandwidth allocation requirements along a path such that data transmission along that path is successful. Using a wireless simulation program known as Qualnet, we analyze the bandwidth efficiency and show that this algorithm provides higher bandwidth guarantees and better overall QoS when compared with solely using RSVP in wireless communication networks.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

LIST OF ACRONYMS AND ABBREVIATIONS

API	Application Programming Interface
DiffServ	Differentiated Service
DoD	Department of Defense
FMSC	Finite State Markov Chain
MANET	Mobile Ad Hoc Network
MPLS	Multi-Protocol Label Switching
OPWA	One-Pass with Advertising
OSPF	Open Shortest Path First
QoS	Quality of Service
RESV	Reserve
RSVP	Resource Reservation Protocol
RSVP-TE	Resource Reservation Protocol Traffic Engineering
SATCOM	Satellite Communication
UGV	Unmanned Ground Vehicle

THIS PAGE INTENTIONALLY LEFT BLANK

ACKNOWLEDGMENTS

First of all, I would like to thank my parents, who live in Turkey. They never withheld their support and belief in me. Even from thousands of miles away, I always felt their confidence in me.

I would like to thank Professor Preetha Thulasiraman for her determination, valuable suggestions and guidance as my advisor. Her background in wireless communication is extensive, and has proven critical to my research. I wish to thank Lt.Col. Joshua D. Green, as my program officer and second reader, for his huge support to help me focus on my thesis. They are the foundation of my success in this thesis.

I would like to express my gratitude to the rest of the NPS staff and my other professors who have given me a tremendous opportunity and inspired me to think outside of the box.

Last, but certainly not least, thanks to the Turkish Navy and its authorities and those who trusted me and sent me to the NPS to get a master's degree. You had provided me the two most beautiful years of my entire life. To all of you, thank you.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

Communication networks have become an integral part of life today. However, one of the main bottlenecks of communication networks is the availability of bandwidth. This is especially true in the wireless environment. Compared with wired/wireline networks, wireless networks offer several advantages over wired networks, such as ease of mobility and speed of deployment, flexibility and, in some cases, reduced costs. Wireless communication has become a pervasive aspect in information technology as there has been a gradual enhancement in quality and security of wireless communication devices together with a decrease in related costs. Although wireless communication is spreading, resources are very scarce. While more wired network/bandwidth is created when new physical resources are added to the communication network, wireless communication requires sharing finite natural resources, specifically, the radio frequency spectrum [1]. In other words wireless devices are constrained to operate in a certain frequency band. This is especially true in the use of wireless technology for defense operations.

In recent years, the Department of Defense (DoD) has dramatically increased the use of mobile wireless communication devices for both tactical and non-tactical applications. One area in which wireless communication has become an important tool is in the deployment of unmanned ground vehicles (UGV). A UGV network operates as an intermittently connected system, distributed over large geographic areas. They function as a cooperative mobile ad hoc network (MANET). This geographic dispersion forces reliance on wireless communication to implement the control systems for the networks. As the number of nodes in the network grows, the bandwidth required to continuously update all nodes may exceed the available bandwidth. This forces system engineers to implement a prioritization scheme to determine which node will be updated during each time frame. This thesis is focused on developing an algorithm for dynamic bandwidth allocation for mobile UGV nodes using basic statistical and network protocols.

A. BASIC CONCEPTS OF WIRELESS COMMUNICATION

To facilitate the discussion of this thesis, this chapter provides an introduction to the basic concepts of wireless communication, particularly the physical and mathematical meaning of bandwidth.

To start the discussion on wireless communication concepts, it is convenient to begin by understanding the main parameter of network performance, known as channel capacity. Channel capacity is the upper boundary on the rate of information that can be transmitted in a communication channel. The channel capacity that a radio frequency channel can support is limited by Shannon’s capacity laws [2].

Bandwidth is generally defined as being a measure of the data capacity of a link. In terms of wireless/digital communication or signal processing the word bandwidth is used to refer to the analog signal bandwidth measured in hertz. In other words bandwidth is the difference between the upper and lower frequencies in a continuous set of frequencies. According to Hartley’s law, the relation between bandwidth and data rate is that the digital data rate limit (or channel capacity) of a physical communication link is proportional to its bandwidth in hertz [3]. In computer networking, bandwidth is a measurement of the bit-rate of available or the consumed data communication resources expressed in bits per second. Each frequency channel has an associated bandwidth which is simply the amount of frequency space in the band. In Figure 1, the spectrum of bandwidth for various frequencies is shown.

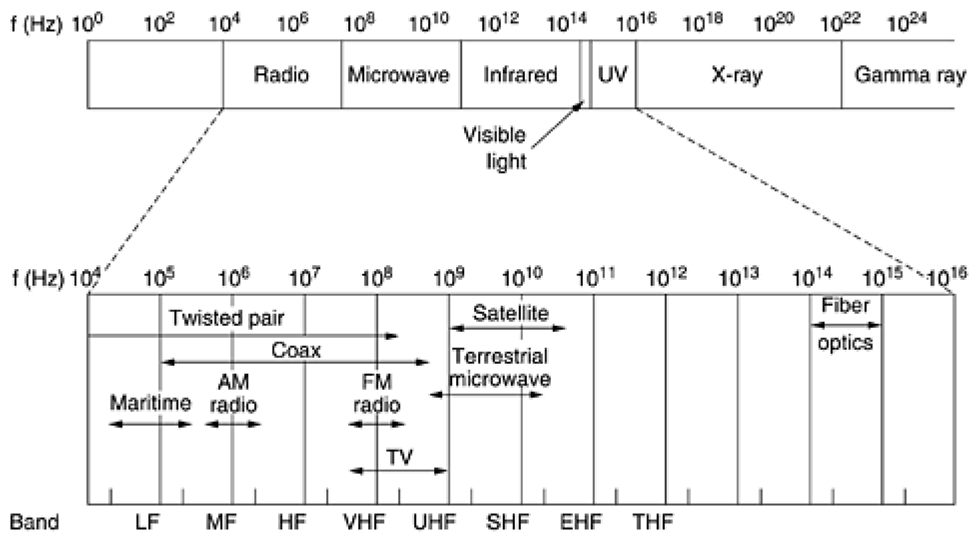


Figure 1. Frequency spectrum for various wireless communication channels from [4].

Channel capacity can be related to bandwidth through the Shannon Hartley theorem given in Equation (1.1),

$$C = B\log_2(1+\frac{S}{N}) \tag{0.1}$$

where C is the channel capacity in bits per second, B is the bandwidth of the channel in hertz, S is the average received signal power measured in watts, N is the average noise or interference power and S/N is the signal to noise ratio. The Shannon formula represents the theoretical maximum capacity that can be achieved [1]. It must be noted that Eq. 1.1 is based on the assumption that the channel is noiseless.

In Equation (1.2), the Shannon-Hartley theorem is re-written assuming that the channel is susceptible to Gaussian Noise (AWGN).

$$C = W\log_2(1+\frac{P}{N_0 W}) \tag{0.2}$$

Here the average received power is denoted as P measured in watts, and the noise power spectral density is N_0 measure in watts per hertz.

B. PROBLEM STATEMENT AND MOTIVATION

An important aspect of wireless communication is efficiency. Efficient network resource management and quality of service (QoS) are parameters that need to be achieved especially when considering network delays. The cooperative nature of UGV networks requires that bandwidth allocation be shared fairly between individual UGV nodes, depending on necessity. Specifically, nodes that require more bandwidth for data transmission should not be starved and arbitrarily limited by bandwidth resources while, conversely, nodes requiring less bandwidth should not be over allocated. This form of bandwidth management is known as statistical multiplexing. In other words, the shared transmission links adapt instantaneously to the traffic demands of the node connected to the link. This dynamic bandwidth allocation takes advantage of several assumptions of cooperative networks:

- All users are typically not connected to the network at one time.
- Even when connected, users are not transmitting data (or voice or video) at all times.
- Most traffic occurs in bursts meaning that there are gaps between the transmission of groups of packets.

While bandwidth allocation schemes for wireless networks have been studied in the literature, UGVs would benefit from implementation of a dynamic bandwidth provisioning scheme. The successful implementation of an efficient bandwidth provisioning algorithm for UGV networks will contribute to helping solve the limited bandwidth problem and prevent failures of UGV nodes in terms of communication.

In this thesis, we study the problem of dynamic bandwidth provisioning in an UGV network. Specifically, we integrate the use of a basic statistical model known as the Markov chain with a widely known, network bandwidth reservation protocol, known as the Resource Reservation Protocol (RSVP).

The Markov chain process is a stochastic process which can be used in various places in wireless communication. The Markov chain process is useful for the following tasks :

- Modeling wireless channels,
- Estimating future traffic demand when nodes are mobile,
- Dynamically allocating bandwidth in a network with varying QoS demands.

RSVP is a transport layer protocol that enables Internet applications to obtain differing QoS for their data flows. It is designed to meet three basic difficulties: achieving higher bandwidth, dealing with real time traffic, and dealing with bursty data. The goals of RSVP can be summarized as follows [5]:

- Accommodate heterogeneous receivers,
- Adapt to route changes,
- Control protocol overhead,
- Use network resources efficiently
- Accommodate heterogeneous underlying technologies

In this regard, RSVP is an ideal candidate for facilitating dynamic bandwidth allocation in UGV networks.

Our aim in briefly introducing the RSVP and Markov chain models above is to illustrate the motivation of using these techniques. Particularly we wish to articulate the basic characteristics of the models and how they are amenable for use in cooperative UGV networks. Specifically, the RSVP does not have a mechanism for traffic demand prediction and the Markov chain process cannot be used as a network tool for bandwidth allocation. Thus, by exploiting the characteristics of both and integrating them, we achieve a more robust and efficient dynamic bandwidth allocation algorithm.

We will expand upon the RSVP and Markov chain process in Chapter III.

C. THESIS CONTRIBUTIONS

The contributions of the research proposed in this thesis lies in the creation of a new algorithm that dynamically allocates bandwidth to node in a UGV network, taking into consideration the channel quality.

This thesis makes the following contributions:

- The Markov chain process is implemented in a UGV network, where each UGV node has some velocity. The Markov Chain model is demonstrated to predict channel conditions at each UGV node. The result of the Markov chain is used to formulate estimated bandwidth requirements.
- The RSVP algorithm is implemented and integrated with the Markov chain process. The Markov chain results are used as input to the RSVP process such that the RSVP algorithm can either increase or decrease the bandwidth requirement at each node. More specifically, the Markov chain results are used with the RSVP to identify specific bandwidth allocation requirements along a path such that data transmission along that path is successful.
- Qualnet, a simulation platform for the wireless environment is used to simulate the algorithm (integration of Markov chain processing with RSVP). We analyze the bandwidth efficiency and show that this algorithm provides higher bandwidth guarantees and better overall QoS when compared with solely using RSVP in the wireless communication networks.

D. ORGANIZATION OF THE THESIS:

The remainder of this thesis is organized as follows. A comprehensive literature review on various aspects of static and dynamic bandwidth allocation in wireless networks is presented in Chapter II. In Chapter III, the general Markov Chain and RSVP algorithms are discussed. The integration of the Markov Chain process and the RSVP algorithm is presented in Chapter IV. Chapter V discusses the performance evaluation and results of the dynamic bandwidth allocation algorithm. The conclusions and directions for future work are provided in Chapter VI. The appendix contains the Qualnet program files used in this research for simulations along with supplementary performance results.

THIS PAGE INTENTIONALLY LEFT BLANK

II. RELATED WORK

In terms of the dynamic bandwidth allocation problem in the wireless communication environment, there are numerous different solutions that exist in the literature. The main goal of these techniques is to increase the QoS and bandwidth efficiency.

A. DYNAMIC BANWIDTH PROVISIONING

There are two types of bandwidth allocation methods: static bandwidth allocation and dynamic bandwidth allocation. Static bandwidth allocation is generally ineffective in terms of QoS. This is because a channel is dedicated some amount of predefined bandwidth, regardless of whether it uses it or not, and thus the bandwidth resources are never released for use by other services. On the other hand, dynamic bandwidth allocation works better in environments in which bandwidth is in high demand.

Dynamic bandwidth allocation is defined in the literature as a technique by which traffic bandwidth in a shared telecommunications medium can be allocated on demand and fairly among different users of that bandwidth. This is a form of bandwidth management, and is essentially the same thing as statistical multiplexing [6].

As part of the bandwidth management process, dynamic bandwidth allocation is an ongoing process. As applications are engaged, the network allocates a portion of the free resources to each of the applications, carefully keeping a balance that ensures each application has sufficient tools to function efficiently. Once a particular application is completed and is no longer active, that bandwidth is freed up and available for use by other applications as needed.

One of the chief benefits of dynamic bandwidth allocation is that applications which may require considerable resources at one point but can function with much less at a later time are automatically adjusted in terms of the amount of bandwidth set aside for the function. In the interim, any bandwidth that remains free can easily be allocated to other resources. This is different from dedicating bandwidth to specific applications since that bandwidth is not available to other applications even when it is not actively used.

B. MARKOV CHAIN PROCESS

A Markov chain is a discrete-valued Markov process. Discrete-valued means that the state space of possible values of the Markov chain is finite or countable. A Markov process is basically a stochastic process in which the past history of the process is irrelevant if the current state is known. In other words, all information about the past and present that would be useful in saying something about the future is contained in the present state.

A discrete-time Markov chain is one in which the system evolves through discrete time steps. Thus, changes to the system can only happen at one of those discrete time values. In a UGV network, the UGV nodes are moving according to an individual mobility pattern. The configuration of the network at a time *t* can be determined to be irrelevant to the past history of the network. The next move of the UGV node can be any direction. The next move only depends on the current position.

A continuous-time Markov chain is one in which changes to the system can happen at any time along a continuous interval. Similar to the discrete Markov chain, the past history is irrelevant to the future state.

The Markov chain process can be used to model the wireless channel since the wireless environment fits the features or specialties of the Markov chain process. In the literature, discrete-time Markov chain models are widely used to analyze transmission mechanisms in wireless networks since techniques for modeling and simulating channel conditions play an essential role in understanding network protocol and application behavior [6]. The wireless channel can be modeled using the Finite State Markov Channel (FMSC). In general, for Markov chains, the set of possible values for each state is a countable set S. If S is finite, it is usually taken to be an integer number as S =

{1,2,3,…,M} and this is an FMSC. In the Markov chain process if the state space is finite, the transition probability distribution of states can be represented by a transition matrix. In [6] and [7], the channel is modeled using a discrete time Markov chain. Similarly in [8] channel modeling is based on N-state Markov chains for satellite communication (SATCOM) systems simulation. The main interest of this modeling is to simulate the wireless environment using a world-wide radio-meteorological databank.

In terms of bandwidth allocation, a Markov chain based model for dynamic bandwidth allocation in a Differentiated Services (DiffServ) network has been proposed [9]. DiffServ is a computer networking architecture that specifies a simple, scalable and coarse-grained mechanism for classifying and managing network traffic and providing QoS on different services. In DiffServ networks, at a timeslot, the proposed Markov chain is used to predict the bandwidth requirement at the next time slot, and the resource (bandwidth) is then allocated accordingly. Such a pre-allocation scheme can effectively reduce the operation overhead in bandwidth allocation and further reduce the connection blocking probability in DiffServ networks.

The Markov chain process can also be used to estimate the future demand in a cell of a cellular network while the nodes are moving to dynamically allocate bandwidth and QoS. Location and request prediction have been analyzed in [10]. The authors conclude that smart wireless networks could deduce future client locations and allocate resources in advance in order to mitigate the negative effect of handovers and perform paging in a cost-effective manner. Furthermore in [11], which also studies cellular networks, the Markov chain process is used to provide dynamic QoS if the applications are capable of adapting to the level of QoS provided by the network, which may vary during the course of a connection. Another similar approach is presented in [12]. The main idea of [12] is the utilization of the bandwidth pre-reservation phase in the admission control protocol through a Markovian approach in order to predict the amount of bandwidth needed by a mobile host during its movements among the cells it will probably visit.

In wireless personal area networks such as wireless body area sensor networks, stations or devices have different bandwidth requirements and thus create heterogeneous networks. The idea presented in [14] represents a general discrete-time Markov chain model for the IEEE 802.15.4-based networks. It takes into account the slotted carrier sense multiple access collision avoidance (CSMA/CA), which is a scheme to control access to the transmission medium [15], and guaranteed time slot (GTS), which is defined as a mechanism for serving devices that required dedicated bandwidth or low latency transmission in the IEEE 802.15.4-based networks. It considers this transmission phenomena together in heterogeneous a traffic scenario and non-saturated condition. For this purpose, the standard GTS allocation scheme is modified. For each non-identical device, the Markov model is solved and the average service time and the service utilization factor are analyzed in the non-saturation mode.

The papers discussed above ([6] to [14]) study the Markov chain process without the implementation of dynamic bandwidth allocation. The literature that studies channel modeling using solely the Markov chain process does not take into consideration the benefit of implementing specific network protocols that will aid in dynamic bandwidth provisioning. In other words, the networking perspective that comes from using an RSVP type protocol has not been considered in the literature. Thus, the approaches studied are purely from a statistical point of view.

C. RESOURCE RESERVATION PROTOCOL

The RSVP is a transport layer protocol that is designed to reserve resources across a network. RSVP is based on signaling messages that traverse the network, allocating resources along the way. RSVP requests resources for simplex (unidirectional communication) traffic flows (i.e, a traffic stream that flows in only one direction from the sender to one or more receivers.) Thus, a bidirectional exchange of data between a pair of nodes actually constitutes two separate RSVP simplex sessions. RSVP is receiver-initiated, because sender initiation does not scale well to large scenarios in which there are heterogeneous receivers. There are two types of primary messages in RSVP. They are path messages and reservation messages. In multicast scenarios, the devices send out only one PATH message to multiple receiving devices, thus conserving network bandwidth [16]. A path message is sent to indicate to the receiver that the sender is requesting an RSVP capable path. Since the RSVP is end to end, the path from sender to receiver must be determined and agreed upon. In other words the resources required along every hop of that path must satisfy the requirements of the sender. Once the PATH message is received by the receiver, it sends back towards the sender a RESV message. The receiver will use the RESV message to request the specific reservation parameters along the path. This is known as QoS reservation. Figure 2 and 3 illustrate the mechanism of RSVP PATH and RESV messages respectively.

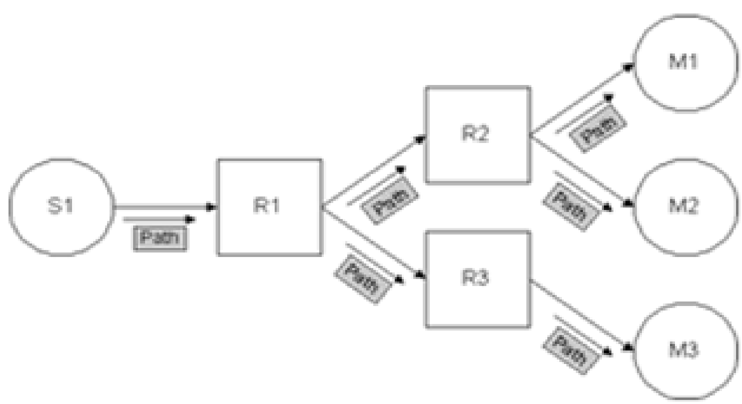


Figure 2. Illustration of the flow of PATH messages from sender (S1) to three different receivers (M1,M2, and M3) via multiple routers (R1, R2, and R3) from [17].

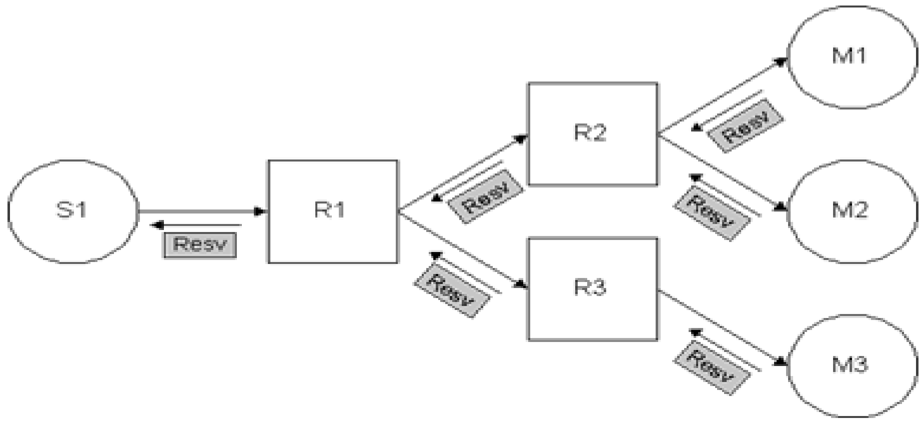


Figure 3. Illustration of the flow of RESV messages from receivers to sender once PATH messages are processed from [17].

It must be noted that RSVP is not a routing protocol but works well with current routing protocols. To obtain the routes, an RSVP process consults the local routing databases. Routing protocols determine where packets get forwarded; RSVP is only concerned with the QoS of those packets that are forwarded in accordance with routing [16].

RSVP is a soft-state protocol, meaning that the reservation must be periodically refreshed or it expires. This supports dynamic automatic adaptation to network changes in order to efficiently accommodate large groups of nodes since the membership of a group and the resulting route path are likely to change with time. The RSVP protocol specifies the creation of “soft states” that can be built and destroyed incrementally in the routers and the hosts. The reservation information, or state, is cached in each hop tasked with managing resources. If the network's routing protocol alters the data path, RSVP attempts to reinstall the reservation state along the new route. When refresh messages are not received, reservations time out and are dropped, releasing bandwidth. The sender refreshes PATH messages, and the receiver refreshes RESV messages. Because RSVP sends its messages as best-effort IP datagrams with no reliability, some messages might be lost, but the periodic transmission of refresh messages by hosts and routers compensates for the occasional loss of an RSVP message. To ensure receipt of refresh messages, the network traffic control mechanism must be statically configured to grant some minimal bandwidth for RSVP messages to protect them from congestion losses. At any time, the sender, receiver or other network device providing QoS can terminate the session by sending a PATH-TEAR or RESV-TEAR message [16].

It is possible that devices along an RSVP path may reject resource requests. If the reservation is rejected due to lack of resources, the requested application is immediately informed that the network cannot currently support that amount and type of bandwidth or the requested service level. The application determines whether to wait and repeat the request later or to send the data immediately using best-effort delivery. QoS-aware applications, generally begin sending new RSVP request messages immediately on a best-effort basis, which is then upgraded to QoS when the reservation is accepted.

RSVP has been upgraded and proposed in a new version called Resource Reservation Protocol-Traffic Engineering (RSVP-TE). It is an extension of the RSVP. RSVP-TE still supports the reservation of resources across an IP network. The differences lie in the ability of RSVP-TE to allow the use of Multi-Protocol Label Switching (MPLS). MPLS is a networking standard designed to speed up network traffic flow. MPLS involves setting up a specific path for a given sequence of packets, identified by a label put in each packet, thus saving the time needed for a router to look up the address of the next node for forwarding. MPLS is called multiprotocol because it works with various network protocols. For this reason, MPLS can carry more and different mixtures of traffic. Using MPLS with RSVP provides a more robust resource allocation mechanism. In this thesis, the RSVP-TE protocol is used for our study. It is also the primary protocol used in Qualnet, the simulation platform used.

THIS PAGE INTENTIONALLY LEFT BLANK

III. GENERAL DISCUSSION OF MARKOV CHAIN ALGORITHM AND RSVP

In this chapter we first give a general idea of the Discrete Time Markov Chain process used in the researched presented in this thesis. We then explain some of the aspects related to our Markov Chain model. We also present a more detailed view of how RSVP works in communication networks.

A. GENERAL VIEW OF MARKOV CHAIN

As was discussed in Chapter II, the Markov chain is a stochastic process. For such a process, the knowledge of the outcome of any preceding node movement does not affect our predictions for the next movement. In this process a set is defined as {X(t), t = 0,1,2,….} whose number of elements is finite and denoted with real positive numbers. Thus, X(t) = i represents that the process is in state i at an instant of time t and takes discrete values. It is said that there is a fixed probability, p_{ij} that indicates the chain going from a state i to a state j in the next time t. This is known as the Markov property [18].

Equation (3.1) is used to illustrate the memoryless property of the Markov chain process. This property indicates that given the present state, the next state is conditionally independent of the past. For a Markov chain, it can be visualized as a process moving from one state to another state [19]. The transitioning between states will be discussed in Section IIIB.

$$P[X(t_k) = X_{k+1} \mid X(t_k = x_k, ..., x(t_1)] = P[X(t_k) = X_{k+1} \mid X(t_k = x_k)] \qquad (0.3)$$

where:

$X(t_k)$,	Current Sample
$X(t_{k+1})$	Future Sample
$X(t_1), ..., X(t_{k-1})$	Past Samples
x_k	State of sample in the moment k.

There are three important elements to Markov Chains;

- Probability Transition Matrix P,
- Transition Diagram
- Steady State Vector π

1. Probability Transition Matrix

The switch between states is established in the probability transition matrix P (in the literature it is also described by T). Each element of the matrix represents the probability that the node switches to another state or remains in the current state. These switches are called transitions. P is a square matrix whose order is the same as the number of states.

Each element of P must satisfy the following two conditions:

$$P_{i,j} \geq 0 \qquad \text{i,j} = 0,1,2,3\ldots. \qquad (0.4)$$

where

$P_{i,j}$ = probability that the current node is in state i given, it was in state j at a time immediately preceding the current time.

i = transition state i.

j = transition state j.

In addition, it is also important that the sum of each row must be equal to one in the transition matrix..

$$\textstyle\sum_i p = 1, \qquad \text{i} = 1,2,3,\ldots\ldots. \qquad (0.5)$$

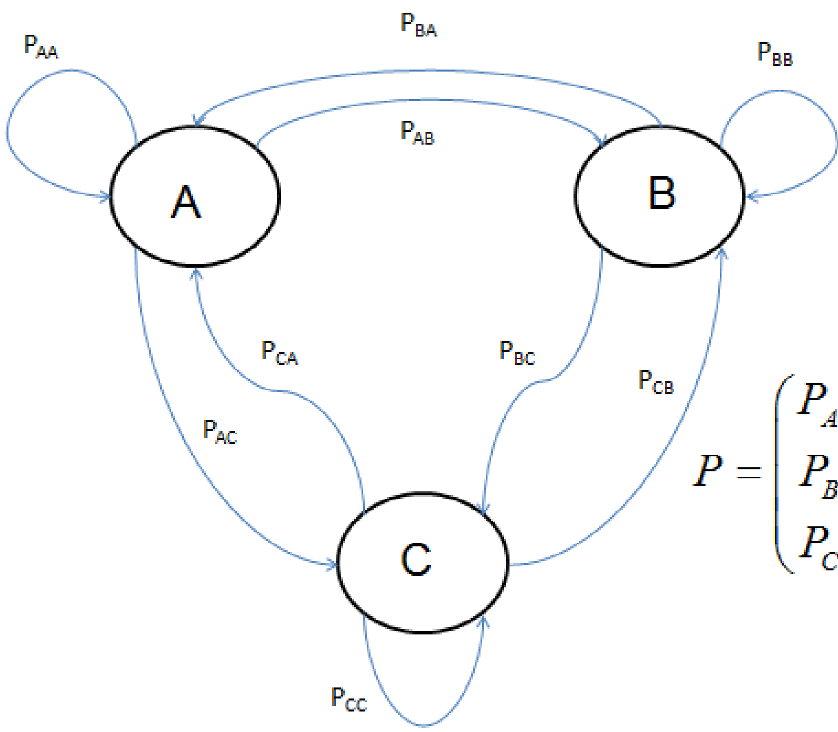
The structure of a probability transition matrix is shown in Figure 3.

$$P_{i,j} = \begin{pmatrix} p_{11} & \cdots & p_{1n} \\ \vdots & \ddots & \vdots \\ p_{n1} & \cdots & p_{nn} \end{pmatrix}$$

Figure 4. Transition matrix for Markov chain with “n” states.

2. Transition Diagram:

A Markov chain transition matrix can be also represented graphically where each node represents a state of the system and is numbered accordingly, and a directed arc connects state i to state j if a one-step transition from i to j is possible. Figure 4 illustrates a typical transition diagram for a system with three states. The corresponding transition matrix is also given.



$$P = \begin{pmatrix} P_{AA} & P_{AB} & P_{AC} \\ P_{BA} & P_{BB} & P_{BC} \\ P_{CA} & P_{CB} & P_{CC} \end{pmatrix}$$

Figure 5. Probability transition diagram for 3 state Markov chain.

3. Steady State Vector:

One of the important elements in the Markov Chain process is the steady state vector π, which represents the total appearing percentage of a state in a Markov Chain. If a system is in steady state, then the recently observed behavior of the system will continue into the future. In stochastic systems, the probabilities that various states will be repeated will remain constant.

Given a square matrix A, we say that the number λ is an eigenvalue of A if there exists a nonzero vector X satisfying AX=λX . In this case, we say that X is an eigenvector of A corresponding to the eigenvalue λ. In terms of the Markov chain process, a steady-state vector of a regular Markov chain is an eigenvector for the transition matrix corresponding to the eigenvalue 1.

The steady state vector can be computed as

$$P^{\pi} \to 1\pi \tag{0.6}$$

where

P Probability transition matrix

π steady state probability vector

1 column vector of ones $1^T = (1,1,\ldots\ldots)$

The sum of its elements must be equal to one as is shown in Eq. 3.5

$$\sum_j \pi = 1 \tag{0.7}$$

The more intricate properties of the Markov Chain, such as reducibility, peridocity, recurrence, ergodicity, have been thoroughly explained in the literature [19],[20],[21],[22]. While these properties are beyond the scope of this thesis, it must be noted that they are important for understanding the dynamics of the Markov chain process.

B. MARKOV CHAIN CHANNEL MODELING

In a typical wireless communication system, the channel conditions vary with time. The transmitted signals are perturbed by additive thermal noise, frequency and time selective fading and interference from other transmitters. Relative mobility between transmitters and receivers causes the channel conditions to change accordingly.

In communication systems, the Markov chain is used to characterize the wireless channel because it represents some of the phenomena that affect the signal during its wireless transmission. Thus, by using a Markov chain, we are able to model a real wireless channel.

A Markov chain is said to be time homogeneous if $P(X_k) = i \mid P(X_{k-1}) = j$ is independent of time index, $\lim_{k\to\infty} p(k) = \pi$

If the Markov chain is time-homogeneous, then the transition matrix P is the same after each step, so the *k*-step transition probability can be computed as the *k*-th power of the transition matrix, P^k.

The following questions are important in the study of the Markov Chain;

a. Does a π so that $\pi = \pi P$? If such a π exists, it is called a stationary distribution.

b. If a unique stationary distribution exists, does $\lim_{k\to\infty} p(k) = \pi$ for all P[0]. In other words does the distribution of the Markov chain converge to the stationary distribution

$$P[X(t_k) = X_{k+1} \mid X(t_k = x_k, ..., x(t_1)] = P[X(t_k) = X_{k+1} \mid X(t_k = x_k)]$$

Since the constant Markov process has the property of stationary transitions, the transition probability is independent of the time index t and can be written as:

$$t = P(X(n+1) = x(k) \mid X(n) = x(j)) \quad (0.8)$$

for all t=0,1,2,… and i,j$\in${0,1,2,…,K-1}.

The model is so characterized by P composed by the $P_{i,j}$ elements, π for which:

$$\pi^t P = \pi^t \qquad (0.9)$$

where π^t is the transpose of π.

In communication networks, the Gilbert-Eliott model is a wireless channel model based on a two-state (bad and good) Markov chain which is widely used for describing burst error patterns in transmission channels. In other words, the Gilbert-Eliott channel is a varying binary symmetric channel with crossover probabilities determined by a binary-state Markov chain process. In a binary symmetric channel, it is assumed that a bit is usually transmitted correctly, but rarely will it be flipped with a small probability called the crossover probability. This crossover probability is denoted as e. The cross over probability is strictly related to physical parameters (such as modulation scheme, carrier frequency and instantaneous user speed)[7].

As mentioned in Chapter II, the wireless channel can be described with a FMSC, completely characterized by its state transition matrix P, steady state vector π, and crossover probability vector e (fixed error). The π and ε (average error probability which can be defined as a probability that a transmitted signal is received in error) do not vary generally during the connection because they are independent from transmission rate and host speed. Matrix P, instead, has the dynamic elements, because they depend on physical parameters such as the wavelength of the carrier signal and transmission rate [7][12].

C. GENERAL VIEW OF RSVP

In this section we give a general idea of how RSVP works and then focus on some important aspects of RSVP, such as refreshment signaling or time and bandwidth reduction.

In RSVP, a data flow is characterized as a sequence of datagrams that have the same source, destination (this could be more than one machine) and QoS. A basic RSVP reservation request consists of two key concepts: flowspec and filterspec. This pair is also called the flow descriptor. RSVP reserves resources for a flow which is identified by the destination address, the protocol identifier (TCP or UDP) and the destination port. The flowspec specifies the desired QoS parameters and is used by the receiver in RESV messages. The flowspec in a reservation request will generally include a service class and two sets of numeric parameters, Rspec and Tspec. Rspec defines the desired QoS, and Tspec describes the data flow [16].

On the other hand, the filterspec defines the set of data packets (the flow) to receive the QoS defined by the flowspec. The flowspec is used to set parameters in the node's packet scheduler, which is a link layer dependent mechanism used to determine which particular packets are forwarded and which achieves the desired QoS for each outgoing interface, while the filterspec is used to set parameters in the packet classifier, which determines the QoS.

During reservation setup, the decision to follow through on an RSVP QoS request is passed to two control mechanisms: admission control and policy control. Admission control determines whether the node has sufficient available resources to supply the requested QoS. Before a reservation can be established, the RSVP process must also consult the policy control to ensure that the reservation is administratively permissible. If both controls succeed, parameters set in the packet scheduler are executed; otherwise, the RSVP returns an error notification.

In RSVP, to make a reservation, RSVP messages carrying reservation requests originate at receivers and are passed upstream towards the sender since RSVP is receiver-oriented as mentioned in Chapter II. At each intermediate node, two actions occur:

- The RSVP passes the request to admission and policy control and the request is executed
- A reservation request is propagated upstream towards the appropriate senders. The set of sender hosts to which a reservation request is propagated is called the scope of that request.

The basic reservation model is one-pass. In this model a receiver sends a request upstream, and at each node in the path the request either is accepted or rejected. This does not provide a way to determine an end-to-end service. Therefore another model is used, known as One-Pass with Advertising (OPWA). With this scheme, RSVP control packets are sent downstream, allowing the flow of data paths to gather information that can be used to predict the end-to-end QoS.

Much of the RSVP's flexibility resides in the vector reservation attributes called the styles. The attributes including the following:

- **Sharing attributes:** There are two types of shared attributes, known as shared and distinct. Shared attributes require that all senders share the same reservation whereas distinct attributes allows receivers to support a distinct reservation for each sender's traffic.
- **Sender selection attributes:** In general, the sender selection attributes control how senders are selected. There are three types of sender selection attributes known as explicit, wildcard and assured. The explicit attribute is used when the RESV filterspec message dictates the explicit selection of senders that will receive the reservation. With the wildcard attribute, RESV has no filterspecs. In other words, all upstream senders can be selected for the reservation. The assured attribute is a hybrid of the wildcard and explicit. Like the explicit attribute, the filterspecs explicitly select those senders that will receive reservation packets, but like the wildcard, the reservations are placed towards all senders, regardless of which senders have been selected.

As explained in Chapter II, there are two types of primary messages in RSVP, PATH messages and RESV messages. These messages are used to allocate enough bandwidth and desired QoS between receiver and sender after using the reservation model and determining reservation styles.

Some aspects of RSVP which we focus on in this thesis are the refreshment signaling, time and RSVP bandwidth reduction. RSVP is a soft-state protocol, which means that the state times out if it is not refreshed soon enough. RSVP maintains state in each node. States of a node need to be periodically refreshed, thus Refresh Messages (actually they are just PATH and RESV messages) are required. These refreshed messages are used for

- State synchronization between neighbor nodes and
- Recovery from lost RSVP messages.

Periodic transmission of refresh messages by nodes (host and routers) is expected to handle the occasional loss of an RSVP message. Suppose that a node generates a RESV refresh every R seconds. The node must randomize the inter-transmission interval, in the range [0.5R, 1.5R] [16],[23]. Note that the value of R is carried in each refresh messages. Suppose that the cleanup timeout is set to K times the refresh timeout period, and T_L is the overall lifetime of state before it is deleted [23]. The equation of lifetime of reservation is;

$$T_L = (K + 0.5) * 1.5 * R \tag{0.10}$$

If K is an integer and R is a constant, then RSVP can tolerate K-1 successive RSVP packet losses without falsely deleting state [16].

In [16], the default K value is 3 and the refresh time is 30 sec. When R is changed dynamically or if the sender increases R rapidly but one or more successive packets is lost, the receiver's node's value of R may be out of date. In [16], this problem is solved by limiting the rate of increase in R. The limit on how fast it may increase depends on the maximum slew ratio, which is a fixed constant that the ratio of R in two successive timeout intervals cannot exceed. Taking into consideration that the maximum slew ratio is 0.3 and the default value of K is 3 as mentioned above, one packet may be lost without state timeout while R is increasing 30 percent per refresh cycle.

Another important aspect of RSVP is bandwidth reduction instead of tearing down the reservation as proposed in [24]. The bandwidth allocated to an individual reservation may be reduced due to a variety of reasons, such as preemption. In some cases, when some of the reservation bandwidth is needed for other purposes, instead of tearing down the reservation, the endpoints can negotiate a new (lower) bandwidth. As given in an example in [24], two aggregate flows with differing priority levels may traverse the same router. If that router reaches bandwidth capacity, the router then has two choices: deny the request or preempt an existing lower priority reservation to make room for the new or expanded reservation. If the flow is preempted, the RSVP clearly does not terminate all the individual flows if an aggregate is torn down [25]. On the other hand [24] describes a method where only the minimum bandwidth is taken away from the lower priority aggregated reservation and the entire reservation is not preempted. A similar approach can be modified for our problem.

When a reservation partially fails, a Reservation Error (ResvErr) message is generated. A new error subcode (the ERROR SPEC) is required and it is added to the ResvErr message. This indicates the flowspec that is reserved. The bandwidth indication in this flowspec should be less than the original reservation request.

IV. INTEGRATION OF MARKOV CHAIN WITH RSVP

In this chapter we first explain the description of our proposed algorithm and then discuss our approach in terms of integrating the Markov chain with RSVP.

A. MODEL DESCRIPTION

In our model, the transition matrix shows the probabilities of changing the states of the link. The initial vector shows (at time t =0) the state between the nodes. Some aspects of our model are discussed in the following sections.

1. Parameter Used to Model Markov Chain Channel

Building a transition matrix and the initial state probability vector is the first step of the Markov chain process. It is essential that the parameter or term which is chosen to exhibit the state transitions behave according to the Markov chain process. In other words it has to have all the necessary properties such as being random, memoryless, etc.

In the literature of wireless communication and channel modeling, the attenuation, the SNR value, and transmission rates are chosen to build the transition matrix [4], [5]. In our model we prefer to choose average transmitted power and average pathloss, which are similar to SNR and attenuation.

2. Building Initial State (Probability Vector)

One of the main steps of the Markov chain process is getting an initial state probability vector since the initial state vector and transition matrix determine the Markov chain process, considering they can build the entire network architecture [13].

The initial state vector is

$p(t) = (P_1 \ldots\ldots\ldots P_N)$ with N being the number of states, and p_i is the probability of starting in each state of the chain.

We get the initial states from our simulation environment.

3. Bandwidth Transition

Our approach to establishing the bandwidth transition is to use the transmission rates and their associate states. This is a similar approach to the one taken in [8]. For a given bandwidth level, the bandwidth transmission model is completely characterized by the matrices such as P (transition probability associated to first/initial state) and M (transition probability associated to the next level).

4. Stationary Distribution

As discussed in Chapter III, in our model, we assume that the Markov chain is time-homogeneous so that the process can be described by a single, time-independent matrix $P_{i,j}$. Then the vector π is called a stationary distribution.

5. Definition of State

In our model we define state as the average transmit power or average pathloss. The state shows the level of power and attenuation so that the transition matrix consists of the probability of decreasing or increasing the power or attenuation level.

6. INTEGRATION OF MARKOV CHAIN WITH RSVP

RSVP is dynamic in terms of node status but it is not dynamic in terms of bandwidth allocation. The Markov chain process is used to make RSVP dynamic considering bandwidth allocation. RSVP uses the output vector of the Markov chain process as feedback that it can use to decide which nodes need bandwidth, and thus, the bandwidth can be allocated dynamically.

The integration of the Markov chain with the RSVP is illustrated by the example shown in Figure 6.

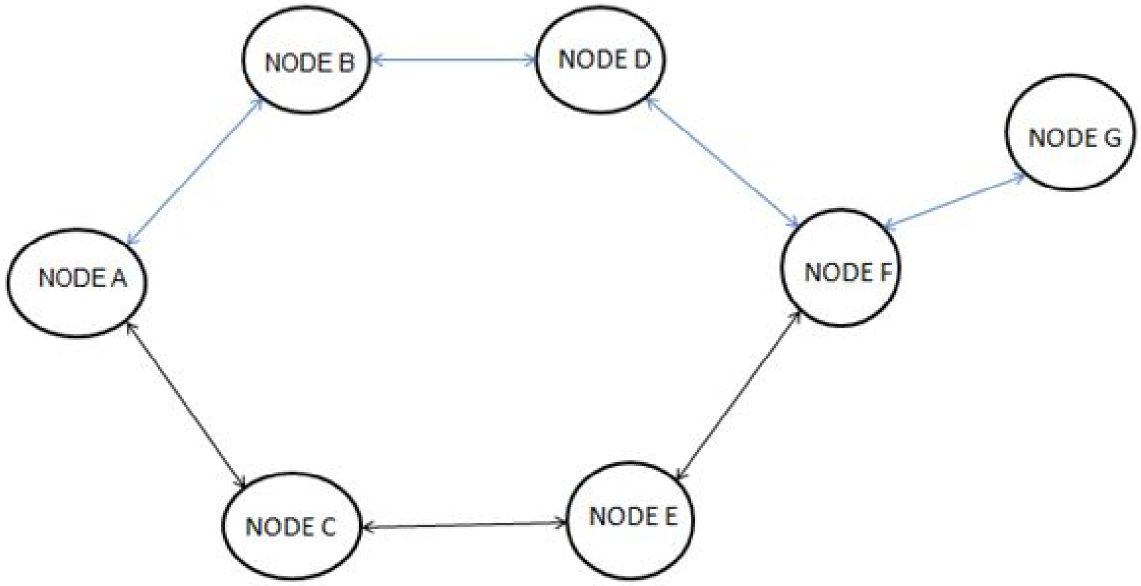


Figure 6. Sample communication network diagram to illustrate the integrated Markov chain and RSVP algorithm.

In this diagram node A wants to send a message to node G. The routing algorithm determines the path (the blue line) and RSVP determines the required bandwidth that the sender requests of the receiver. Note that the routing algorithm used in this thesis is either Open Shortest Path First (OSPF) or Bellman-Ford [25],[26].

The state of a node is; based on the assumption that the channel quality (transmit power or path loss in our model) is between 20 dB and 50dB. In that case, the difference between states is 3dB. The first state is 20-23dB, and the next state is 23-26db. By adding 3dB for each state, the last state has a channel quality of 47-50dB.

The transition probability matrix has the probabilities of switching states. The first step is to modify the probability transition matrix by computing the cumulative sum for each row since this will determine the transition between states.

At time t=0, we have the initial and transition matrices and the initial probability vector. The Markov chain process uses the random walk procedure which is a mathematical formulization of a path that consists of a succession of random steps that are discrete and of fixed length.

The second step is choosing a random value, which is then compared with the modified transition matrix.

- If the random value is lower than the current value, the state is decreased by one.
- If the random value is higher than the current value but lower than the next value, the link between the nodes remains the same.
- If it is higher than the next value, the state increases by one.

For instance, assuming that the state of the link between node A to node B in Figure 6 is 4. The probability of changing state is 0.4. The state remains the same if the random value is 0.3. If the random value is 0.5, the state of the link increases by one and becomes 5.

If the transition matrix is stationary, the state will converge to a number in the Markov Chain process. This allows us to determine the future state of that link. As an example, at time t=0, the minimum state level is 3. At time t=n, the minimum state level would converge to state 6. By taking into consideration this change, the allocated bandwidth between sender and receiver can be increased or decreased.

The output vector of this process shows us how this wireless network will be shaped. After the process, we will deduce and give feedback to RSVP about whether to increase or decrease the bandwidth or remain the same.

The steps for the Markov chain algorithm are as follows;

1. Define the transition matrix and the initial vector.
2. Define the output vector
3. Define the state of the Markov chain process
4. Obtain a random value between 0 and 1.

5. Take the first value of the initial vector and use this random value and the initial value and compare it to the transition matrix value.

    a) Check whether this is the first or last state (it behaves differently in different cases).

    b) If the random value is lower than the transition matrix value, decrease the state by one.

    c) If it is equal or higher than current value but lower than next value, the state stays the same.

    d) If it is higher than the next value, the state increases by one.

6. Find the output vector.

7. If it is stationary, find when and to which number output vector will converge.

Step 5 is repeated as many times as necessary until the output vector ends.

After the Markov chain calculates the state of the channel, feedback can be given to RSVP using the output vector. In order to allocate bandwidth dynamically, this thesis proposes two methods:

- Use refresh messages which are sent periodically, so that reserved bandwidth can be decreased or increased.
- Reduce bandwidth using the model proposed in [24].

THIS PAGE INTENTIONALLY LEFT BLANK

V. PERFORMANCE AND EVALUATION

In this chapter, we presented the results of a simulation study, conducted in Qualnet, a wireless communication simulation platform. We use the simulations to demonstrate and validate the Markov chain and RSVP integrated algorithm described in Chapter IV. As a benchmark, we use the traditional RSVP algorithm to compare against the integrated Markov Chain and RSVP algorithm presented in this thesis. The comparative analysis will allow us to understand whether the integrated approach provides significantly better results than the traditional RSVP.

A. SIMULATION DESCRIPTION

We simulate four different simulation networks that consist of 5, 10, 15 and 30 nodes, respectively. The scenario dimension is 1500 m X 1500 m. The altitude is 1500m above sea level. Different simulation times are chosen, specifically 5 sec, 30 sec, 5 min and 30 min since there needs to be at least 5-10 sec for the Markov chain process to run effectively. The mobility model of nodes is random way point that simulates the movement of the UGV nodes. The node maximum speed is 10 meter per second (mps). The chosen routing protocols are Bellman-Ford and OSPF. The buffer size is 16384 bytes. The subnets are designed using different numbers of nodes and different distances. Instead of using a real terrain environment, the default wireless terrain data is applied. The exact lists of these parameters of simulation are shown in Table 1.

Table 1. Simulation parameters used in Qualnet.

TERRAIN		NETWORK LAYER	
Coorinate System	Cartesian	Network Protocol	IP
Terrain Dimension	1500,1500	ROUTING PROTOCOL	
Altitude	1500,0	Routing Protocol	Bellman Ford-OSPF
Weather Mobility	10S	TRANSPORT PROTOCOL	
CHANNEL PROPERTIES		TCP Sender/Receiver Buffer	16384
Propagation Channel Frequency	2.4 GHZ	BATTERY MODEL	
Propagation Model	Statistical	Battery Model	None
Prop. Pathloss Model	Two-Way	MAC LAYER	
Prop. Shadowing Model	Constant	Link Prop. Delay	1MS
Prop. Shadowing Mean	4.0	Link Bandwidth	10MB
Prop. Fading Model	None	Link RX/TX Frequency	13.17 GHz
Prop. Speed	3e8	Link RX/TX Antenna Height	30 M
Prop. Limit	-111.0	Link TX Power	30
Prop. Max. Distance	0	Link RX Sensitivity	-80
Prop. Comm. Proximity	400		
Propogation Update Ratio	0		
PHYSICAL LAYER			
PHY Model	PHY 802.11b.	PHY 802.11b Data Rate	1,2,6,11 MB
PHY 802.11b Tx Power	15	PHY 802.11b Rx Power (for each different data rate)	-94, -91, -87, -83
Antenna Model	Omnidirectional	Antenna Gain	0
Antenna Height	1.5	Antenna Efficiency	0.8
Antenna Mismatch Loss	0.3	Antenna Cable Loss	0
Antenna Conncetion Loss	0.2	PHY Temperature	290 K
PHY Noise Factor	10		

An example wireless network simulated in Qualnet with 15 nodes and their respective subnets is shown in Figure 7.

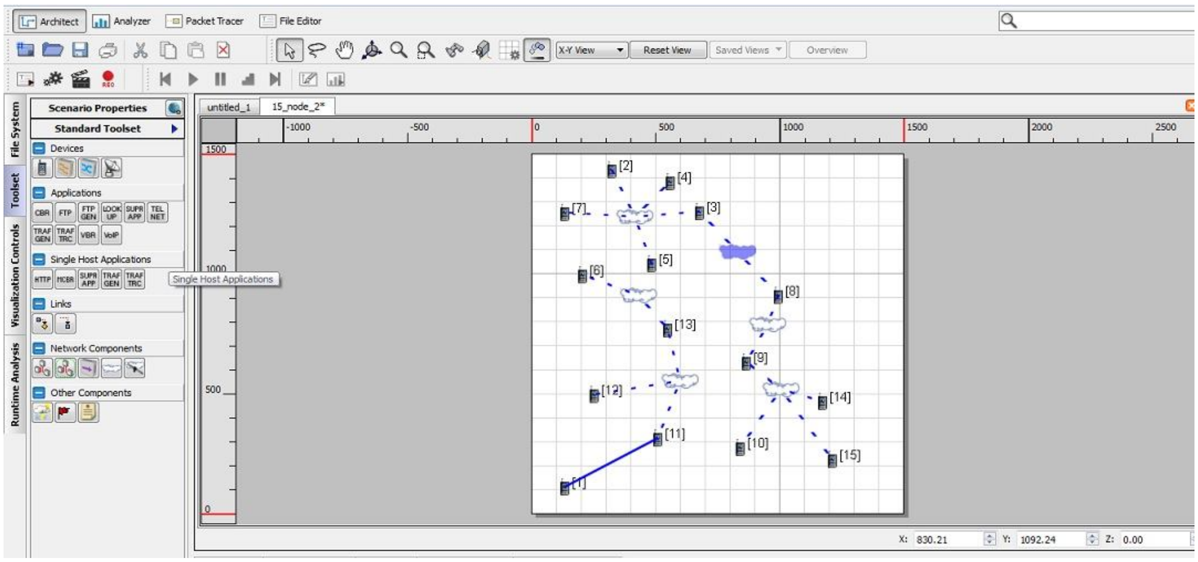


Figure 7. An example wireless communication network consist of 15 nodes that was simulated in Qualnet. The dashed lines represent the wireless connectivity between nodes within a subnet.

B. SIMULATION RESULTS AND ANALYSIS

The performance metrics used for analysis are average signal power, average pathloss and node utilization. These parameters are as follows:

Average Signal Power: Average signal power is measured in dBm from the beginning of simulation up to the specified time in the Timestamp column. These values are chosen to be 5 sec, 30 sec, 5 min and 30 min in our simulations.

Average Pathloss: Average pathloss (in dB) is the reduction in the power density (attenuation) of the signal. In the simulations it is a measure from the physical layer at the beginning of the simulation up to the line specified in the Timestamp column.

Node Utilization: Average utilization of the nodes in terms of power measured from physical layer from the beginning of the simulation up to the time specified in the Timestamp column.

A total of 34 simulations were executed. Due to space constraints, we are showing a subset of the simulations. The results shown depict the main simulations that reflect the best results that will allow comparison and analysis.

1. 5-Node Wireless Communication Network

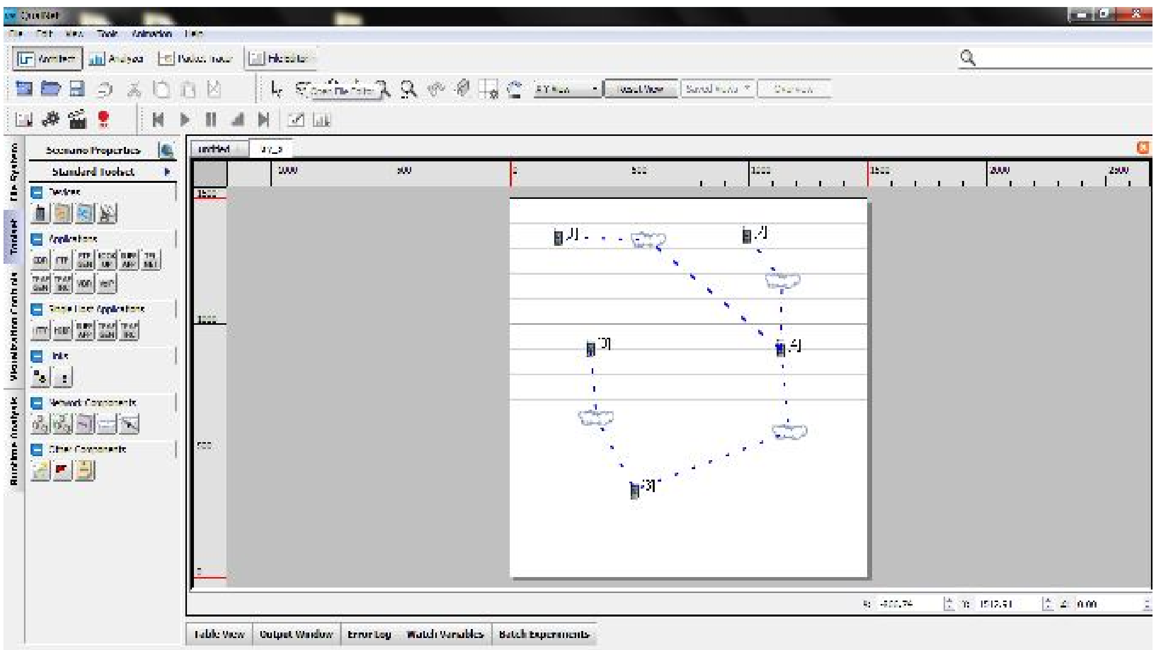


Figure 8. The 5-node wireless network simulated in the Qualnet environment.

The simulation time is 30 min and the chosen data rate is 2 mbps for the 5-node network, as shown in Figure 8. The average power/pathloss results of this network are shown in Table 2.

Table 2. 5-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-76	3	89	8
2	-80	2	95	9
3	-75	3	91	9
4	9	10	42	4
5	6	10	62	6

The average power is between -91 dB to 12 dB. We define the state level as 10dB and the state of -99 to -90 dB is 1 and the state of -89 to 80 dB is 2 and so on. This is similar to when we consider average pathloss. Looking at the results, we can see that the change of average pathloss on node 4 and 5 is quite large (i.e., 9 to 42 and 6 to 62, respectively). Although the chosen path can be seen by looking at the table because there are merely 5 nodes, it is difficult to designate the path for large networks. Since in the Markov chain process, the transition probability matrix consists of the probability of switching state, it helps us to determine which state is going to change. Here the path is

Path: 1-4-5

After the Markov chain process is executed, we get the results shown in Table 3.

The simulation time is 30 min and the data rate increased to 11 mbps for those nodes on the path. The comparative results are shown in Table 3.

Table 3. Results before and after Markov chain process for a 5 node network with the data path 1-4-5. Node utilization and BER results after the Markov chain (AMC) and before the Markov chain (BMC).

NODE	UTILIZATION (BMC)	BER (BMC)	UTILIZATION (AMC)	BER (AMC)
1	0.000023	330/2454	0.000039	299/2556
4	0.0033	325/2563	0.00057	141/2546
5	0.00513	280/2264	0.00623	225/2332

The node utilization and the bit error rate (BER) at node 4 and 5 increase slightly. With these results it is difficult to gauge whether the integration of the Markov chain with integrated RSVP works better or worse than RSVP alone. This is specifically due to the small network size.

2. 10-Node Wireless Communication Network

The next simulation network studied is a 10-node network shown in Figure 9.

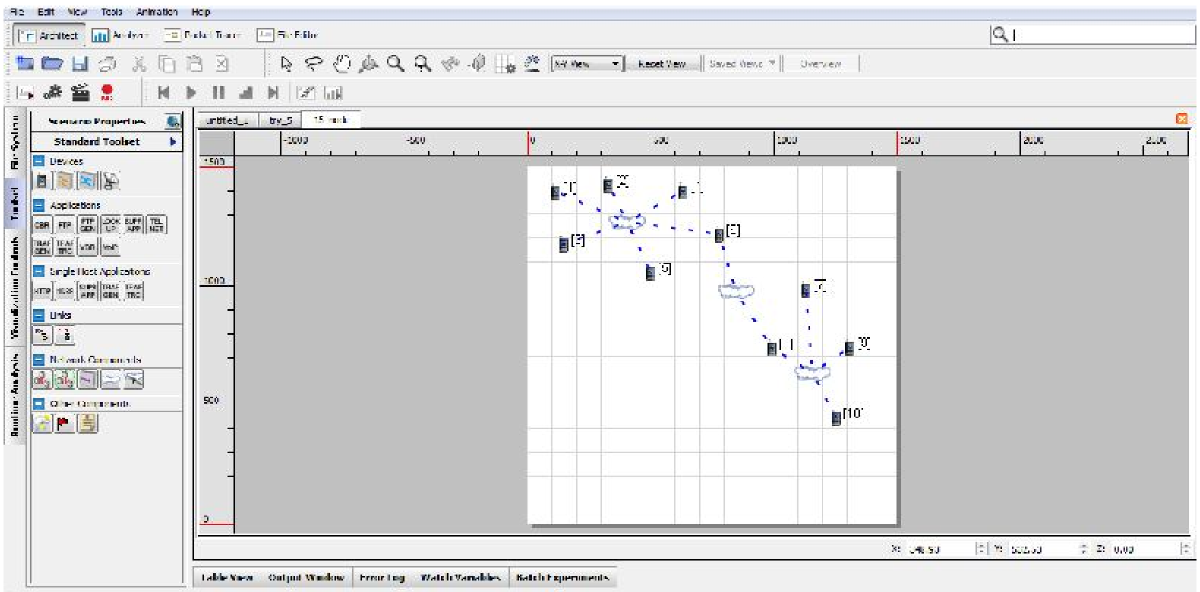


Figure 9. The 10-node wireless network simulated in the Qualnet environment.

The simulation time is 30 min, and the chosen data rate is 2 mbps for the 10-node network. The average power/pathloss results are shown in Table 4.

Table 4. 10-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-76	3	90	9
2	-74	3	94	9
3	-58	5	91	9
4	-72	3	90	9
5	-81	2	94	9
6	7	10	56	5
7	-77	3	91	9
8	7	10	56	5
9	-76	3	92	9
10	-75	3	90	9

The average power is between -87 dB to 7 dB. We define the state level as 10dB. The state of -99 to -90 dB is 1 and the state of -89 to 80 dB is 2 and so on. We use a similar approach for average pathloss value. The Markov chain process takes into consideration the average loss and calculates that node 6 and node 8 will transition to a new state. The path in which the states are changed is chosen as

Path: 2-6-8-10

The simulation time is 30 min, and the data rate increased to 11 mbps for those nodes on the path. The comparative results are shown in Table 5.

Table 5. Results before and after Markov chain process for a 10 node network with the data path 2-6-8-10. Node utilization and BER results after the Markov chain (AMC) and before the Markov chain (BMC).

NODE	UTILIZATION (BMC)	BER (BMC)	UTILIZATION (AMC)	BER (AMC)
2	0.0002	879/2892	0.0003	954/3489
6	0.0003	748/2975	0.0004	682/3241
8	0.0003	775/3164	0.0003	685/3315
10	0.0026	725/3263	0.0022	734/3474

After we modify the simulation, the node utilization does not change but BER decreases. It can be concluded here that in terms of BER, the integration of Markov Chain process with RSVP works better.

3. 15 Node Wireless Communication Network

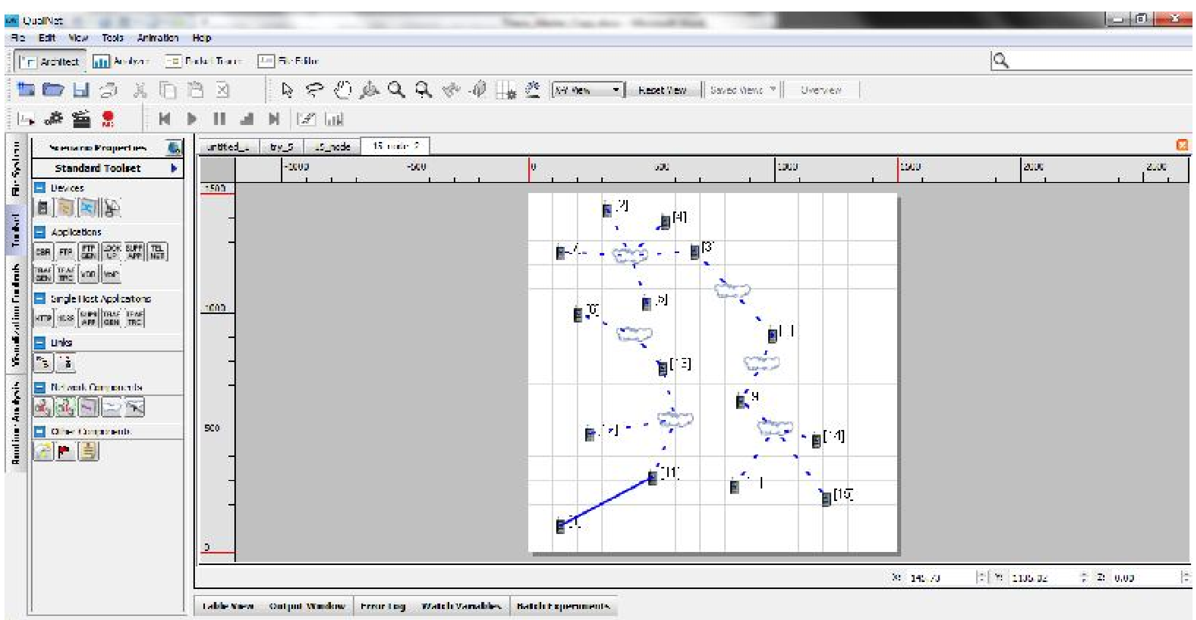


Figure 10. The 15 node wireless network simulated in the Qualnet environment.

The next network studied is a 15-node network, as shown in Figure 10. The simulation time is 30 min and the chosen data rate is 2mbps for the 15-node network. The average power/pathloss results are shown in Table 6.

Table 6. 15 node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-	-	-	-
2	-72	3	91	9
3	3	10	69	6
4	-75	3	90	9
5	3	10	71	7
6	-78	3	92	9
7	-80	2	93	9
8	4.8	10	63	6
9	3.9	10	68	6
10	-77	3	91	9
11	-77	3	92	9
12	-74	3	92	9
13	3.6	10	70	7
14	-77	3	92	9
15	-75	3	91	9

The state level is 10 dB. The Markov Chain process takes into consideration the average loss and calculates that node 6 and node 8 is going to have new state. The path in which nodes level are changed is chosen as

Path: 3-8-9-15

The simulation time is 30 min and the data rate is increased to 11 mbps for those nodes on the path. The comparative results are shown in Table 7.

Table 7. Results before and after Markov chain process for a 10 node network with the data path 3-8-9-15. Node utilization and BER results after the Markov chain (AMC) and before the Markov chain (BMC).

NODE	UTILIZATION (BMC)	BER (BMC)	UTILIZATION (AMC)	BER (AMC)
3	0.003353	2657/9824	0.001044	2530/8990
8	0.002838	2056/10026	0.002012	1385/9130
9	0.002442	1677/9949	0.001303	1641/9189
15	0.003141	2295/10297	0.003141	2126/9436

4. 30 Node Wireless Communication Network

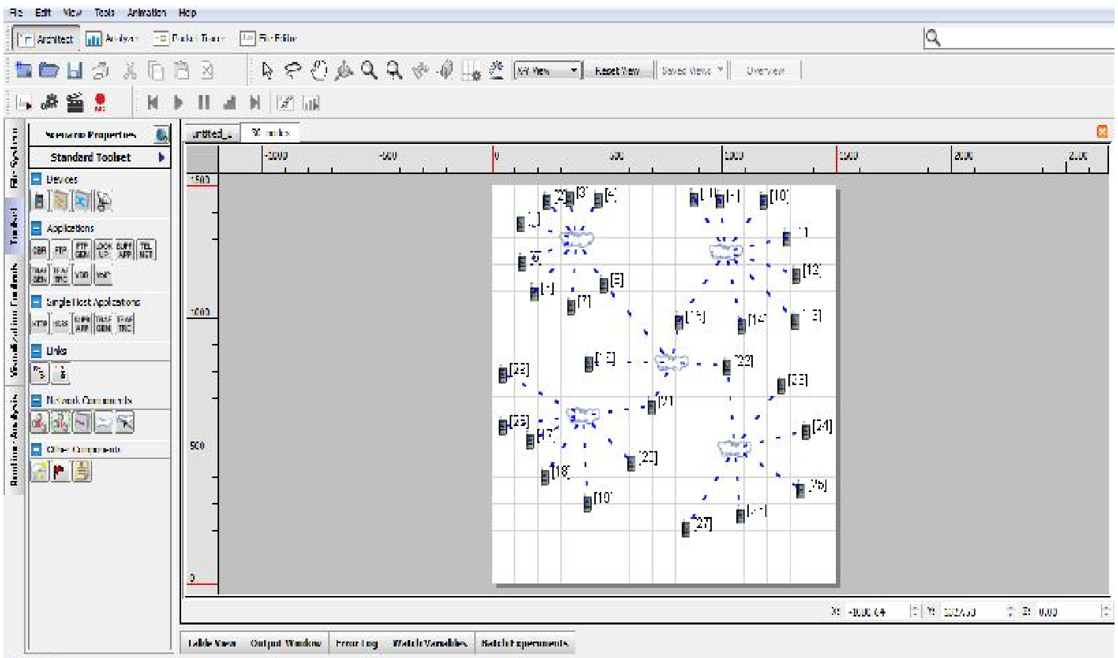


Figure 11. Tnode wireless network simulated in the Qualnet environment.

The average power/pathloss results are shown in Table 8.

Table 8. 30 node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-76	3	90	9
2	-75	3	90	9
3	-77	3	91	9
4	-76	3	90	9
5	-78	3	90	9
6	-68	4	88	8
7	-77	3	91	9
8	3	10	71	7
9	-75	3	90	9
10	-75	3	90	9
11	-70	3	91	9
12	-76	3	91	9
13	-76	3	90	9
14	-74	3	92	9
15	2.3	10	70	7
16	-78	3	91	9
17	-78	3	91	9
18	-75	3	89	8
19	-64	4	89	8
20	-76	7	91	9
21	2.8	10	70	7
22	2.5	10	72	7
23	-75	3	91	9
24	-79	3	91	9
25	-77	3	90	9
26	-76	3	91	9
27	-77	3	90	9
28	-69	3	90	9
29	-81	2	92	9
30	-78	3	91	9

After the Markov Chain process runs, the path chosen to analyze is

Path: 2-8-21-18

The simulation time is 30 min and the data rate increased to 11 mbps for those nodes on the path. The comparative results are shown in Table 9.

Table 9. Results before and after Markov chain process for a 30-node network with the data path 2-8-21-18. Node utilization and BER results after the Markov chain (AMC) and before the Markov chain (BMC).

NODE	UTILIZATION (BMC)	BER (BMC)	UTILIZATION (AMC)	BER (AMC)
2	0.005366	8194/28445	0.002870	9150/27274
8	0.004020	4323/27684	0.002098	4916/26605
21	0.004214	5232/27818	0.002321	4711/26686
18	0.003141	5828/28377	0.002446	6505/27223

When we compare the 5-node network and the 30-node network and when we compare the 5 sec to 30 min simulation results, it can be said that the simulations results make more sense as the number of nodes and simulation time increases. This is particularly true for the, 5-second simulation time, which results in more nuanced results than for other simulations (30 sec, 5 min and 30 min).

Although the approach and results are scientifically correct, it should be noted that there are some limitations due to the Qualnet simulation program. The most important limitation is that Qualnet supports only four data rates (2,4,8,16 mbps) in the 802.11b wireless simulation environment. This limitation restricts the transition of bandwidth effectively.

Changing routing algorithms does not affect the results much when the number of nodes is low. For instance the 5 node network's average power/pathloss and utilization/BER results are shown for Bellman Ford and OSPF [26],[27] in Tables 10-13.

Table 10. Power/pathloss results using the Bellman Ford routing algorithm for the 5 node network where the simulation time is 30 sec.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-91	1	0	-
2	-88	2	97	9
3	-91	1	0	-
4	10	11	12	1
5	12	11	0	-

Table 11. Power/pathloss results using the OSPF routing algorithm for the 5 node network where the simulation time is 30 sec.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-90	1	0	-
2	-89	2	97	9
3	-91	1	0	-
4	10	11	7	1
5	12	11	0	-

Table 12. Node utilization and BER results for using Bellman Ford routing algorithm for the 5 node network where the simulation time is 30 sec.

NODE	UTILIZATION (BMC)	BER (BMC)	UTILIZATION (AMC)	BER (AMC)
1	0.000022	6/42	0.000019	7/48
4	0.0035	8/42	0.0035	5/49
5	0.0023	3/43	0.0023	3/46

Table 13. Node utilization and BER results for using the OSPF routing algorithm for the 5 node network where the simulation time is 30 sec.

NODE	UTILIZATION (BMC)	BER (BMC)	UTILIZATION (AMC)	BER (AMC)
1	0.000015	6/42	0.000021	7/49
4	0.00033	5/42	0.0036	4/48
5	0.000015	1/42	0.0019	4/48

The 30-node power/pathloss and node utilization and BER results are shown in Tables 14-17 for Bellman Ford and OSPF. It can be seen that the differences are much bigger than for 5-node network.

Table 14. Power/pathloss results using the Bellman Ford routing algorithm for the 30-node network where the simulation time is 30 sec.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-79	3	92	9
2	-75	3	90	9
3	-71	3	90	9
4	-72	3	91	9
5	-80	2	92	9
6	-80	2	93	9
7	-81	2	92	9
8	0.9	10	78	7
9	-79	3	86	8
10	-82	2	92	9
11	-80	2	89	8
12	-80	3	88	8
13	-82	2	91	9
14	-82	2	91	9
15	0.7	10	76	7
16	-84	2	95	9
17	-75	3	90	9
18	-75	3	91	9
19	-84	2	93	9
20	-84	2	93	9
21	0.8	10	64	6
22	0.9	10	77	7
23	-81	2	91	9
24	-81	2	89	8
25	-83	2	92	9
26	-83	2	92	9
27	-85	2	93	9
28	-79	2	89	8
29	-81	2	93	9
30	-81	2	86	8

Table 15. Power/pathloss results using the OSPF routing algorithm for the 30-node network where the simulation time is 30 sec.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-78	3	90	9
2	-73	3	87	8
3	-72	3	88	8
4	-72	3	87	8
5	-78	3	89	8
6	-77	3	88	8
7	-77	3	89	8
8	1.8	10	76	7
9	-80	2	86	8
10	-84	2	91	9
11	-79	3	89	8
12	-79	3	89	8
13	-80	2	90	9
14	-80	2	91	9
15	-2.4	9	79	7
16	-84	2	92	9
17	-77	3	89	8
18	-73	3	87	8
19	-82	2	92	9
20	-86	2	93	9
21	1.1	10	74	7
22	2.6	10	68	6
23	-81	2	90	9
24	-78	3	87	8
25	-85	2	92	9
26	-86	2	91	9
27	-87	2	90	9
28	-79	2	88	8
29	-83	2	90	9
30	-81	2	88	8

When we compare the result of average power and pathloss between the Bellman Ford and OSPF, the states of many nodes are different. For instance node 21 and node 22 have difference states considering pathloss. The node 21 average pathloss for Bellman Ford is 64dB, so the state is 6, and it is 74dB for OSPF, so the state is 7. Node 22 is also similar.

Table 16. Node utilization and BER results for using Bellman Ford routing algorithm for the 30-node network where the simulation time is 30 sec.

NODE	UTILIZATION (BMC)	BER (BMC)	UTILIZATION (AMC)	BER (AMC)
2	0.0002	91/563	0.005	62/596
8	0.0003	216/585	0.009	143/624
21	0.003	216/589	0.008	135/624
18	0.0001	48/594	0.003	44/628

Table 17. Node utilization and BER results for using the OSPF routing algorithm for the 30-node network where the simulation time is 30 sec.

NODE	UTILIZATION (BMC)	BER (BMC)	UTILIZATION (AMC)	BER (AMC)
2	0.009	411/3174	0.04	341/3111
8	0.01	1073/3298	0.05	715/3372
21	0.01	949/3325	0.04	744/3120
18	0.003	204/3260	0.001	114/3298

THIS PAGE INTENTIONALLY LEFT BLANK

VI. CONCLUSION AND FUTURE WORK

A. CONCLUSION

Communication networks have become an integral part of life today. However, one of the main bottlenecks of communication networks is the availability of bandwidth. This is especially true in the wireless environment. Another important aspect of wireless communication is efficiency. Efficient network resource management and quality of service (QoS) are parameters that need to be achieved especially when considering network delays. The cooperative nature of UGV networks require that bandwidth allocation be shared fairly between individual UGV nodes, depending on necessity.

In this thesis, we study the problem of dynamic bandwidth provisioning in an UGV network. Specifically, we integrate the use of a basic statistical model, known as the Markov chain with a widely known, network bandwidth reservation protocol, known as the Resource Reservation Protocol (RSVP). The Markov chain results are used with RSVP to identify specific bandwidth allocation requirements along a path such that data transmission along that path is successful. We analyze the bandwidth efficiency and show that the integration of the Markov chain with RSVP provides higher bandwidth guarantees and better overall QoS when compared with using RSVP alone in wireless communication networks.

In our performance evaluation, we simulated four different network environments that have the same parameters. The algorithm is shown to have better node utilization and BER when the Markov chain predicts future channel conditions and determines what bandwidth requirements are needed. The results from the Markov chain process are then used with RSVP to reserve the appropriate bandwidth along individual paths. We have demonstrated that RSVP works better when the Markov chain is integrated with it as compared to when only RSVP is used for bandwidth guarantees.

B. FUTURE WORK

In this thesis, we integrate the Markov chain process with RSVP. RSVP is built into the Qualnet simulator and the Markov chain program is written separately and then they are integrated manually. A potential future work can be to integrate them in the Qualnet environment. The Qualnet simulator allows this approach. The dynamic Application Programming Interface (API) in the Qualnet environment allows users and programs to modify and monitor a Qualnet simulation dynamically. Using the dynamic API, a user or program can change values of variables and can be notified when statistics change during execution. The dynamic API operates between the external interface API (from the perspective of this thesis, this can be the Markov chain process) and the simulation. The external interface API is responsible for communicating with the external program and sending commands from the external program to the dynamic API. The dynamic API interacts with the Qualnet simulation, giving the results of commands back to the external interface, API, in turn, sends results back to the external program [28]. Due to time considerations, this method was not pursued in this thesis.

Another reason that the Markov chain process with RSVP should be integrated into the Qualnet environment is that the work that has been done in this thesis uses the values of the Markov Chain and RSVP, and then those values are changed accordingly. So, in some sense it is not necessarily dynamic. A more pure dynamic approach in which the system actually changes with each time t when a new bandwidth allocation is requested should be studied. In this thesis we can only look at small node networks because we are studying and obtaining the measurements first before making the bandwidth allocation. An integrated approach using Qualnet, may help in network scale as well (looking at larger networks of 100 nodes).

The modeled scenario is limited in scope, and future work can be spent working on more expanded scenarios. Although it can be more difficult to analyze, the dimension of the network area or the number of nodes can be increased to get more real time values.

It needs to be noted that in future work, another simulator such as OPNET can be used. This can avoid some of the Qualnet limitations such as data rate types.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A. SUPPLEMENTAL SIMULATION RESULTS

This appendix provides the supplemental simulations results that were analyzed but due to space not included in Chapter 5.

A. SIMULATION RESULTS FOR 5 NODE WIRELESS COMMUNICATION NETWORK

The average power is between -91 dB to 12 dB. We define the state level as 10dB and The state of -99 to -90 dB is 1 and the state of -89 to 80 dB is 2 and so on. This is similar when we consider average pathloss.

1. Simulation Time : 5 sec, Data Rate : 2mbps

Table 18. 5-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-91	1	0	-
2	-91	1	0	-
3	-91	1	0	-
4	10	11	0	-
5	12	11	0	-

2. Simulation Time : 30 sec, Data Rate : 2mbps

Table 19. 5-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-91	1	0	-
2	-88	2	97	9
3	-91	1	0	-
4	10	11	12	1
5	12	11	0	-

3. Simulation Time : 5 min, Data Rate : 2 mbps

Table 20. 5-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-88	1	96	9
2	-75	3	92	9
3	-72	3	91	9
4	10	11	17	1
5	7	10	25	2

4. Simulation Time : 30 min, Data Rate : 2 mbps

Table 21. 5-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-76	3	89	8
2	-80	2	95	9
3	-75	3	91	9
4	9	10	42	4
5	6	10	62	6

THE PATH: 1-4-5

5. Simulation Time : 30 min, Data Rate : 11 mbps

Table 22. Results before and after Markov Chain process for a 5 node network with the data path 1-4-5. Node utilization and BER results after the Markov Chain (AMC) and before the Markov Chain (BMC).

NODE	UTILIZATION (BMC)	BER (BMC)	UTILIZATION (AMC)	BER (AMC)
1	0.000023	330/2454	0.000039	299/2556
4	0.0033	325/2563	0.00057	141/2546
5	0.00513	280/2264	0.00623	225/2332

B. SIMULATION RESULTS FOR 10-NODE WIRELESS COMMUNICATION NETWORK

1. Simulation Time : 5 sec, Data Rate : 2mbps

Table 23. 10-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-81	2	90	9
2	-83	2	94	9
3	-83	2	95	9
4	-83	2	94	9
5	-87	2	98	9
6	3	10	68	6
7	-84	2	96	9
8	3	10	74	7
9	-84	2	96	9
10	-86	2	97	9

2. Simulation Time : 30 sec, Data Rate : 2mbps

Table 24. 10-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-82	2	91	9
2	-82	2	93	9
3	-83	2	95	9
4	-82	2	94	9
5	-86	2	97	9
6	3	10	71	7
7	-83	2	95	9
8	4	10	68	6
9	-84	2	96	9
10	-87	2	98	9

3. Simulation Time : 5 min, Data Rate : 2mbps

Table 25. 10-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-85	2	93	9
2	-69	4	93	9
3	-78	3	93	9
4	-63	4	93	9
5	-84	2	95	9
6	6	10	63	6
7	-76	3	91	9
8	6	10	60	6
9	-77	3	92	9
10	-80	2	94	9

4. Simulation Time : 30 min, Data Rate : 2mbps

Table 26. 10-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-76	3	90	9
2	-74	3	94	9
3	-58	5	91	9
4	-72	3	90	9
5	-81	2	94	9
6	7	10	56	5
7	-77	3	91	9
8	7	10	56	5
9	-76	3	92	9
10	-75	3	90	9

Path: 2-6-8-10

Table 27. Results before and after Markov Chain process for a 10 node network with the data path 2-6-8-10. Node utilization and BER results after the Markov Chain (AMC) and before the Markov Chain (BMC).

NODE	UTILIZATION (BMC)	BER (BMC)	UTILIZATION (AMC)	BER (AMC)
2	0.0002	879/2892	0.0003	954/3489
6	0.0003	748/2975	0.0004	682/3241
8	0.0003	775/3164	0.0003	685/3315
10	0.0026	725/3263	0.002265	734/3474

C. SIMULATION RESULTS FOR 15 NODE WIRELESS COMMUNICATION NETWORK

1. Simulation Time : 5 sec, Data Rate : 2mbps

Table 28. 15-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-	-	-	-
2	-84	2	94	9
3	1.7	10	75	7
4	-81	2	93	9
5	2.2	10	78	7
6	-85	2	95	9
7	-84	2	94	9
8	2.6	10	63	6
9	3	10	77	7
10	-86	2	98	9
11	-88	2	97	9
12	-87	2	97	9
13	1	10	86	8
14	-85	2	97	9
15	-86	2	96	9

2. Simulation Time : 30 sec, Data Rate : 2mbps

Table 29. 15-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-	-	-	-
2	-79	3	94	9
3	2.1	10	70	7
4	-78	3	93	9
5	1.7	10	80	8
6	-85	2	96	9
7	-85	2	95	9
8	3.03	10	66	6
9	2.5	10	76	9
10	-85	2	97	9
11	-87	2	96	9
12	-87	2	96	9
13	1.3	10	80	8
14	-87	2	96	9
15	-87	2	95	9

3. Simulation Time : 5 min, Data Rate : 2mbps

Table 30. 15-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-	-	-	-
2	-81	2	94	9
3	3	10	71	7
4	-77	3	91	9
5	3.5	10	73	7
6	-82	2	94	9
7	-79	3	92	9
8	3.03	10	72	7
9	2.5	10	76	7
10	-79	3	92	9
11	-73	3	91	9
12	-78	3	92	9
13	2.8	10	73	8
14	-85	2	95	9
15	-80	2	93	9

4. Simulation Time : 30 min, Data Rate : 2mbps

Table 31. 10-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-	-	-	-
2	-72	3	91	9
3	3	10	69	6
4	-75	3	90	9
5	3	10	71	7
6	-78	3	92	9
7	-80	2	93	9
8	4.8	10	63	6
9	3.9	10	68	6
10	-77	3	91	9
11	-77	3	92	9
12	-74	3	92	9
13	3.6	10	70	7
14	-77	3	92	9
15	-75	3	91	9

Path : 3-8-9-15

Table 32. Results before and after Markov Chain process for a 10 node network with the data path 3-8-9-15. Node utilization and BER results after the Markov Chain (AMC) and before the Markov Chain (BMC).

NODE	UTILIZATION (BMC)	BER (BMC)	UTILIZATION (AMC)	BER (AMC)
3	0.003353	2657/9824	0.001044	2530/8990
8	0.002838	2056/10026	0.002012	1385/9130
9	0.002442	1677/9949	0.001303	1641/9189
15	0.003141	2295/10297	0.003141	2126/9436

D. SIMULATION RESULTS FOR 30 NODE WIRELESS COMMUNICATION NETWORK

1. Simulation Time : 5 sec, Data Rate : 2mbps

Table 33. 30-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-79	3	92	9
2	-78	3	90	9
3	-77	3	91	9
4	-81	2	92	9
5	-80	2	93	9
6	-80	2	93	9
7	-81	2	91	9
8	0.2	10	81	8
9	-80	2	87	9
10	-80	2	90	9
11	-80	2	88	8
12	-81	3	88	8
13	-82	2	91	9
14	-82	2	91	9
15	0.6	10	78	7
16	-86	2	96	9
17	-78	3	91	9
18	-80	2	92	9
19	-84	2	93	9
20	-83	2	92	9
21	0.5	10	42	4
22	1.8	10	77	7
23	-82	2	92	9
24	-83	2	90	9
25	-82	2	92	9
26	-84	2	93	9
27	-85	2	94	9
28	-80	2	90	9
29	-83	2	94	9
30	-81	2	85	8

2. Simulation Time : 30 sec, Data Rate : 2mbps

Table 34. 30-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-79	3	92	9
2	-75	3	90	9
3	-71	3	90	9
4	-72	3	91	9
5	-80	2	92	9
6	-80	2	93	9
7	-81	2	92	9
8	0.9	10	78	7
9	-79	3	86	8
10	-82	2	92	9
11	-80	2	89	8
12	-80	3	88	8
13	-82	2	91	9
14	-82	2	91	9
15	0.7	10	76	7
16	-84	2	95	9
17	-75	3	90	9
18	-75	3	91	9
19	-84	2	93	9
20	-84	2	93	9
21	0.8	10	64	6
22	0.9	10	77	7
23	-81	2	91	9
24	-81	2	89	8
25	-83	2	92	9
26	-83	2	92	9
27	-85	2	93	9
28	-79	2	89	8
29	-81	2	93	9
30	-81	2	86	8

3. Simulation Time : 5 min, Data Rate : 2mbps

Table 35. 30-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-80	2	91	9
2	-78	3	91	9
3	-76	3	90	9
4	-77	3	90	9
5	-77	3	90	9
6	-75	10	89	8
7	-79	3	92	9
8	1.1	10	75	7
9	-75	3	90	9
10	-79	3	91	9
11	-77	3	89	8
12	-78	3	90	9
13	-74	3	89	8
14	1.9	10	74	7
15	-78	3	91	9
16	-78	3	90	9
17	-78	3	90	9
18	-78	3	90	9
19	-83	2	93	9
20	-79	3	92	9
21	1.5	10	73	7
22	2	10	73	7
23	-82	2	91	9
24	-79	3	91	9
25	-75	3	90	9
26	-76	3	89	8
27	-75	3	89	8
28	-80	2	91	9
29	-82	3	93	9
30	-78	3	90	9

4. Simulation Time : 30 min, Data Rate : 2mbps

Table 36. 30-node network average power/pathloss results.

NODE	AVR. POWER	STATE	AVR. PATHLOSS	STATE
1	-76	3	90	9
2	-75	3	90	9
3	-77	3	91	9
4	-76	3	90	9
5	-78	3	90	9
6	-68	4	88	8
7	-77	3	91	9
8	3	10	69	6
9	-75	3	90	9
10	-75	3	90	9
11	-70	3	91	9
12	-76	3	91	9
13	-76	3	90	9
14	-74	3	92	9
15	2.3	10	70	7
16	-78	3	91	9
17	-78	3	91	9
18	-75	3	89	8
19	-64	4	89	8
20	-76	7	91	9
21	2.8	10	70	7
22	2.5	10	72	7
23	-75	3	91	9
24	-79	3	91	9
25	-77	3	90	9
26	-76	3	91	9
27	-77	3	90	9
28	-69	3	90	9
29	-81	2	92	9
30	-78	3	91	9

Path: 2-8-21-18

Table 37. Results before and after Markov Chain process for a 10 node network with the data path 2-8-21-18. Node utilization and BER results after the Markov Chain (AMC) and before the Markov Chain (BMC).

NODE	UTILIZATION (BMC)	BER (BMC)	UTILIZATION (AMC)	BER (AMC)
2	0.005366	8194/28445	0.002870	9150/27274
8	0.004020	4323/27684	0.002098	4916/26605
21	0.004214	5232/27818	0.002321	4711/26686
18	0.003141	5828/28377	0.002446	6505/27223

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX B. MARKOV CHAIN CODE IN QUALNET ENVIRONMENT

This appendix provides the code for the Markov Chain, which is written in C ++ in the Qualnet environment.

```
/***********************************************************************
*********
*
*mchain:Finite State Markov Chain Process
*main (command line parsing and database implementation)
*
*purpose:   To estimate next states of channel
*author:    Yavuz SAGIR
*Date First Writen : 5 April 2013
*Date Last Modified : 10 May 2013
************************************************************************
********/

#include <iostream>
#include <fstream>
#include <cstring>
#include <cstdlib>
#include <iomanip>
#include <string>
#include <time.h>

using namespace std;

//const int MAXSTATE = 15;
const int lengthChain = 15;

//parameters
int channel[15];//output vector is
double action;  //randomly generated number with which compare it to
double P1[15][15];

// read TransMatrix function reads the initial transition matrix from
the file before executing the Markov Chain process

void readTransMatrix (const char* trans_matrix)
{
 FILE* file = fopen (trans_matrix, "r");
 char i[80];
 double d =0;
```

```
 fscanf (file, "%s", &i);
 while (!feof (file))
    {
       d = atof (i);
       printf ("%f ", d);
       fscanf (file, "%s", &i);
    }
  fclose (file);
}

//printInitial function prints the initial transition matrix
void printInitial()
{
  printf("the initial values of P1 :\n");
  for (int i=0;i<=14;i++)
  {
     double temp = 0;
     for (int k=0;k<=14;k++)
     {
     P1[i][k] = (rand()%101)/100.0;
     printf("%f-",P1[i][k]);
     }
     printf("\n");
  }
}
//printOutputVector  shows  the  output  vector  after  the  Markov  chain
process is executed.
void printOutputVector()
{
  for (int i=0;i<=14;i++)
      {
         printf("%d - ",channel[i]);
      }
}

int main(int argc, char *argv[])
      {
  /* initialize random seed: */
  srand (time(NULL));

  //printing the initial matrix
    printInitial();
```

```
//for (int i=0;i<=lengthChain;i++) //check every row
//{
int i = channel [0];  //assign channel's first member to row

for (int t=1;t<=15;t++) //discrete time steps such as t=0, t=1.....t=n
{
  for (int j = 1;j<=lengthChain;j++)  //check every column
  {
    action = rand() % 101;
    action = action/100.0;  //generate a number between 0 and 1
    if  ((i  ==  0)&(action  <P1[i][j]))//previous  sample  is  just  first
value and compare random number and transition matrix
    {
       channel [j] = 1;
       printf("1 is assigned to channel, no switch\n");
    }
    else if ((i == 0)&(action>P1[i][j+1]))
    {
       channel [j] = 3;
       printf("3 is assigned to channel, increase\n");
    }
    else
    {
    channel [j] = 2;
      printf("2 is assigned to channel\n");
    }

    if ((i == lengthChain-1)&(action <P1[i][j]))
    {
       channel [j] = 1;
       printf("1 is assigned to channel, last to first\n");

    }
    else if ((i == lengthChain-1)&(action >P1[i][j+1]))
    {
       channel [j] = lengthChain;
       printf("last value of chain is assigned to channel\n");
    }
    else
    {
    channel [j] = lengthChain-1;
      printf("the last value is checked, no change\n");
    }

    if  (action  <P1[i][j])   //compare  random  value  and  the  transition
matrix
        {
        channel[j] = i-1;
        printf("when the value of j is : %d, decrease one\n",j);
        }
        else if (action > P1[i][j])
        {
           channel[j] = i+1;
           printf("when the value of j is : %d, increase one\n",j);
        }
```

```
        else
        {
           channel[j] = i;
           printf("when the value of j is : %d, no switch\n",j);
        }
     }
  printf("time step : %d\n",t);

      for (int i=0;i<=14;i++)
      {
         printf("%d - ",channel[i]);
      }
}
//}
//printf channel state output vector
  printf("channel state output vector :\n");
  printOutputVector();
  system("pause");
}
```

LIST OF REFERENCES

[1] X. Liu, “Oppotunistic scheduling in wireless communication network,” Ph.D. dissertation, Purdue Univ, West Lafayetta, IN, 2012.

[2] W. Stallings, “Transmission Fundemantals,” Wireless Communications and Networking, 2nd ed. New Jersey, NY: Prentice Hall, 2002, ch. 2, pp. 28–32.

[3] J. Martin and J. Leben, *Data Communication Technology*,New Jersey, NY: Prentice Hall, pp. 112, 1988.

[4] M. Humphyrs, “Wireless Network Notes,” School of Computing, Dublin City University. Available: http://computing.dcu.ie/~humphrys /Notes/Networks/physical.wireless.html.

[5] L. Zhang, S. Deering, D. Estrin, S. Shenker, and D. Zappala,” RSVP: A New Resource Reservation Protocol,” *IEEE Network*, pp. 8–18, September 1993.

[6] A. Konrad, B. Y. Zhao, A. D. Joseph, R. Ludwig,”A Markov-Based Channel Model Algorithm for Wireless Networks,” *Wireless Networks, vol. 9,* pp. 189–199, 2003.

[7] H. S. Wang, N. Moayeri, “Finite-State Markov Channel – A Useful Model for Radio Communication Channels,” *IEEE Transactions on Vehicular Technology*, vol. 44, no. 1, pp. 163–171, February 1995.

[8] L. Castanet, T. Deloues, J. Lemorton, “Channel Modelling Based on N-State Markov Chains for SATCOM Systems Simulation” *Browse Conf. Publications, Antennas and Propagation*, vol. 1, pp. 119–122, 2003.

[9] X. Geng, A. Luo, Z. Sun, and Y. Cheng, “Markov Chain Based Dynamic Bandwidth Allocation in DiffServ Network,” *IEEE Communications Letters*, vol. 16, no. 10, pp. 1711–1714, October 2012.

[10] D. Katsaros, Y. Manolopoulos, “Prediction in Wireless Networks by Markov Chains,” *IEEE Wireless Communications*, pp. 56–63, April 2009.

[11] M. Mirhakkak, N. Schult, D. Thomson, “Dynamic Bandwidth Management and Adaptive Applications for a Variable Bandwidth Wireless Environment,” *IEEE Journal on Selected Areas in Communications*, vol. 19, no. 10, pp. 1984–1997, October 2001.

[12] P. Fazio, M. Tropea, F. Veltri, S. Marano, “A Novel Rate Adaptation Scheme for Dynamic Bandwidth Management in Wireless Networks,” *IEEE 75th Vehicular Technology Conference*, 2013.

[13] B. Shrestra, E. Hossain, S. Camorlinga, “A Markov Model for IEEE 802.15.4 MAC with GTS Transmissions and Heterogeneous Traffic in Non-saturation Mode,” *Communication Systems (ICCS), 2010 IEEE International Conference*, 17–19 November 2010

[14] M. S. Cast, *802.11 Wireless Networks*, 1st ed. Sebastopol, CA: O’reilly, 2002.

[15] R. Braden, L. Zhang, S. Berson, S. Herzog, S. Jamin, *Resource ReSerVation Protocol (RSVP) - Version 1 Functional Specification*, IETF RFC 2205, September 1997; http://www.rfc-editor.org/rfc/rfc2205.txt.

[16] W. Stallings. *Data and Computer Communications*, 9th Ed. New Jersey, NY: Prentice Hall, 2011.

[17] J. K. Kemeny, J.L. Snell, *Finite Markov Chains*, Van Nostrand, NJ Princeton, 1960.

[18] J.R Norris, *Markov Chains*, United Kingdom, Cambridge University Press, 1987.

[19] Y. Suhov, M. Kelbert, *Probability and Statistics by Example : Volume 2, Markov Chains, A primer in Random Processes and Their Applications*, Cambridge, United Kingdom, Cambridge University Press,2008.

[20] P. Bremaud, *Markov Chains : Gibbs Fields, Monte Carlo Simulation and Queues*, New York, NY, Springer Science Business Media, 2010.

[21] R.,S.Moss, Stochastic Processes, John Wiley and Sons, 1996.

[22] R. Braden, D. Estrin, S. Berson, S. Herzog, D. Zappala, “The Design of the RSVP Protocol,” USC/Information Sciences Institute, June 1995 Available: http://www1.cs.columbia.edu/~hgs/papers/others /rsvp.final.report.pdf

[23] J. Polk, S. Dhesikan, *A Resource Reservation Protocol (RSVP) Extension for the Reduction of Bandwidth of a Reservation Flow*, IETF RFC 4495, May 2006; http://www.rfc-editor.org/rfc/rfc4495.txt.

[24] F. Baker, C. Iturralde, F. Le Faucheur, B. Davie, *Aggregation of RSVP for IPv4 and IPv6 Reservations*, IETF RFC 3175, September 2001; http://www.rfc-editor.org/rfc/rfc3175.txt.

[25] J. Moy, *OSPF Version 2*, IETF RFC 2328, April 1998; http://www.rfc-editor.org/rfc/rfc2328.txt.

[26] C.L. Hedrick, *Routing Information Protocol*, RFC 1058, June 1988, http://www.rfc-editor.org/rfc/rfc1058.txt.

[27] *Qualnet 6.1 Programmer's Guide*, Scalable Network Technologies, pp. 457, September 2012

THIS PAGE INTENTIONALLY LEFT BLANK

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California